GPS INSTRUMENTATION IN BALLISTIC MISSILE INTERCEPT TEST AND EVALUATION

Thomas Thompson

Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723

Abstract

GPS instrumentation capable of measuring a missile intercept event with less than 2-centimeter accuracy has been demonstrated in a special high speed/acceleration sled test at Holloman AFB. Although the basic instrumentation technique is well defined, plans to properly exploit this capability are yet to be adequately addressed. This paper reviews the demonstrated differential GPS instrumentation technique that achieves 2-centimeter accuracy and then discusses the factors that need be addressed to properly exploit this capability. It describes the important and unique attributes of high-precision GPS measurements in regard to missile intercept evaluation. The difference between accurate GPS end-game trajectory measurements and a direct impact-point measurement are contrasted to emphasize the benefits of the GPS methodology. The basis for the preferred translator-based versus receiver-based GPS instrumentation is discussed with particular attention to the risk benefit of the translator approach. The challenges of GPS instrumentation on the interceptor are discussed with suggested implementation alternatives related to antenna design, digital versus analog translator design, dual versus single frequency use, and GPS signal bandwidth. Finally, an instrument configuration is described that can achieve the desired measurement accuracy with minimum risk.

Review

Background

A large body of test and application data is available to demonstrate that GPS measurements can provide relative position determinations with millimeter precision. Most of the evidence has been restricted to applications with low relative-motion dynamics. Some specialized testing has used acceleration-restricted sled tests and some have used turntable techniques to assess higher-level acceleration limits of GPS instrumentation available for missile intercept testing. The only true test of relative GPS measurements in an intercept environment are those gathered from two early Integrated Flight Test (IFT) projects referred to as Exoatmospheric Reentry Intercept Subsystem (ERIS) tests.[1] These two tests demonstrated that a target and an interceptor each equipped with GPS translators could be positioned relative to each other in the intercept region with an accuracy of less than 60cm.

A 2-cm GPS Intercept Measurement Capability

The tracking data from the ERIS test were further analyzed to determine if fractional wavelength (i.e., on the order of 2cm accuracy) relative positioning could be achieved. Those analyses indicated that the restrictions imposed by the specific GPS instrumentation used in ERIS would not allow reliable cycle ambiguity resolution, which is required to achieve the fractional wavelength positioning accuracy. An alternate GPS translator was proposed for this application, based on using the complete GPS signal spectrum (both frequencies and each with their full 20MHz bandwidth). Using an available translator, its receiving and recording equipment, and post processing subsystem, the wide bandwidth concept was tested in a special test at the Holloman high-speed test track. This high-dynamic sled test demonstrated that 2cm accuracy could be achieved in an intercept environment. However, there are currently no plans to incorporate this capability into future intercept tests.

Issues With Proven GPS Capability

Bandwidth

The largest single issue usually raised against implementing the proven GPS translator approach is that it requires too much downlink bandwidth. The downlink bandwidth of this approach is a fundamental part of the reasons for its benefit and it cannot be largely compromised. Most of the resistance is based on thinking of the translator output signal as part of system telemetry. The translator output is not telemetry; it is more like a radar transponder output than a telemetry transmitter output (i.e., the satellites

This document is approved for public release; distribution is unlimited.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
29JUL2002	N/A	-

Title and Subtitle GPS Instrumentation in Ballistic Missile Intercept Test and Evaluation	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Johns Hopkins University Applied Physics Laboratory Laurel, MD 20723	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es)	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes See Also ADM201460. Papers from Unclassified Proceedings from the 11th Annual AAIA/MDA Technology Conference held in Monterey, CA from 29 Jul - 2 Aug 2002., The original document contains color images.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 8	

are the "radar transmitters" and the ground station is the receiver). Since GPS translators are now replacing range radar for the range safety function, why not allocate space in the radar band for GPS translator outputs? Even the full GPS signal bandwidth is small relative to most radar bandwidths and in the range safety application the GPS translator exactly replaces the function of a C-band radar transponder.

GPS Receiver Alternative

Another issue that has slowed implementation of a GPS translator system is the belief that a GPS receiver will eventually do just as well and it has a very small telemetry requirement. The problem with this thinking is that the receiver needed to approach the capability of the translator system is not practical and, even if it were, it will always carry a higher risk of failure. Given the precious nature of intercept test data, the translator approach is the preferred choice. There are several reasons, beyond the risk comparison, that recommend the translator approach. These are discussed later.

Telemetry and Impact Measurements

Some believe the normal interceptor telemetry data supplemented with target-mounted impact detection instrumentation having 2cm-accuracy is sufficient. After all, the interceptor design is challenging enough with regard to size and weight constraints. In this case, however, all high accuracy information is derived by working backwards from where the impact is detected, there is no accuracy data provided from tests with near misses or impacts outside the instrumented impact zone. Whereas precision trajectory data covering the closing geometry will provide valuable accuracy information from all test flights and will provide more complete impact geometry information for the successful impacts. In any event, the weight and size characteristics of the required instrumentation are quite modest; it is hard to believe that this problem can't be solved with sufficient determination.

Based on our understanding of the test and evaluation objectives for ballistic missile intercept tests, we are convinced that wide bandwidth translator-based GPS instrumentation should be a standard part of all interceptor flight tests.

Range Safety Connection

A major focus on GPS translator work in recent years comes out of the Range Instrumentation System Program Office (RISPO) program for development of the Translated GPS Range System (TGRS). The natural emphasis within this development activity has been on assuring adequate range safety performance to replace the current radar range safety systems that will be taken off line in the next several years. However, the range safety accuracy requirement can be satisfied with a GPS translator design that is not adequate for the high-accuracy end-game trajectory measurements that are the focus of this paper.

TGRS Translators

For example, the only TGRS translator flight tested so far operates with single frequency 1.6MHz GPS signal. This translator provides less accuracy than the translators used in the ERIS program (this conclusion has been demonstrated with side-by-side comparisons from recent missile flight tests). There is no expectation that this translator will provide relative trajectory measurements with 2cm-accuracy. The 1.6MHz GPS translator can be configured for dual frequency, but analysis indicates that this choice will also not meet requirements.

The next TGRS choice is a translator that provides 3.2MHz GPS signals and it can be either single- or dual-frequency. This translator only offers a marginal improvement relative to the ERIS translator, it requires 8MHz downlink bandwidth, and it will still not provide the data required for high-accuracy post-flight processing.

The next TGRS choice provides 6.4MHz GPS signals and it can be single- or dual-frequency. This translator is not likely to meet accuracy objectives (i.e., it represents a high-risk for accuracy performance). Furthermore it requires a 16MHz downlink bandwidth and an analog translator using this same bandwidth would be nearly equivalent to the analog translators successfully used in the Holloman demonstration (i.e., a low-risk approach). The TGRS translator that provides 16MHz GPS bandwidth requires 40MHz downlink bandwidth.

GPS Antenna Configuration

There is also an issue with regard to GPS antenna designs. Antenna phase modeling is more important for the post processing accuracy objective than it is for the range safety objective. Based on the antenna designs that are currently emerging, it must be assumed that accuracy analysis requirements have had little or no input to antenna design. What is needed is a design that simultaneously address range safety and accuracy requirements.

Holloman Demonstration

The Holloman demonstration is discussed in several earlier papers.[2,3,4] This section will provide a brief review of the test configuration and rocket sled dynamics, and summarize the important test results.

The test included two *full-signal-bandwidth* GPS translator equipped bodies, one rocket propelled on one rail and the other stationary on the second rail. Both bodies used the same type GPS antenna. The dynamic body used two S-band blade antennas, one to relay the translated GPS signals to the Track Data Center (TDC) and the second for telemetry signals. S-band translator signals from the stationary body were carried by cable to a trackside blockhouse. Translated GPS signals were recorded at both sites using specially developed receiver/recording equipment.

The need to provide a high speed intercept-like test condition with a controlled and accurately measured trajectory, led to selection of the Holloman high-speed test track. Figure 1 shows the basic geometry and defines the measurement coordinate system. Relative position vector measurements are defined in terms of three orthogonal components *(along-track, cross-track, vertical)*. The origin is at the center of the stationary body's GPS antenna. The surveyed relative position vector at closest approach is (0, 2.133, 0) meters. The high dynamic conditions as derived from an on-board accelerometer are shown in Figure 2. The dynamic body reached Mach 4 at Time-of-Closest-Approach (TCA).

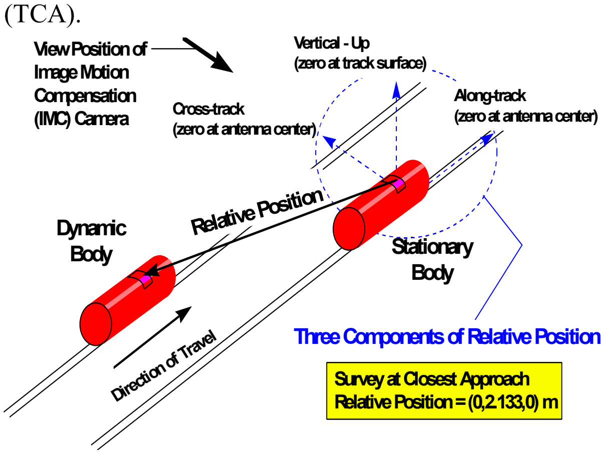

Figure 1. Relative position vector geometry.

An optical measurement system implemented and operated by the Holloman test team provided for an independent measurement of the relative position vector in the region of closest approach. Positions along the track were based on cutting fiber optic cables at surveyed positions on the track surface. The positions of each fiber cable break were accurate to a small fraction of an inch. The absolute time of any break was accurate to less than 2 microseconds and the relative time between breaks to less than 200 nanoseconds. The system also used a high-speed image motion compensation camera that captures a picture of the sled geometry at the point of closest approach.

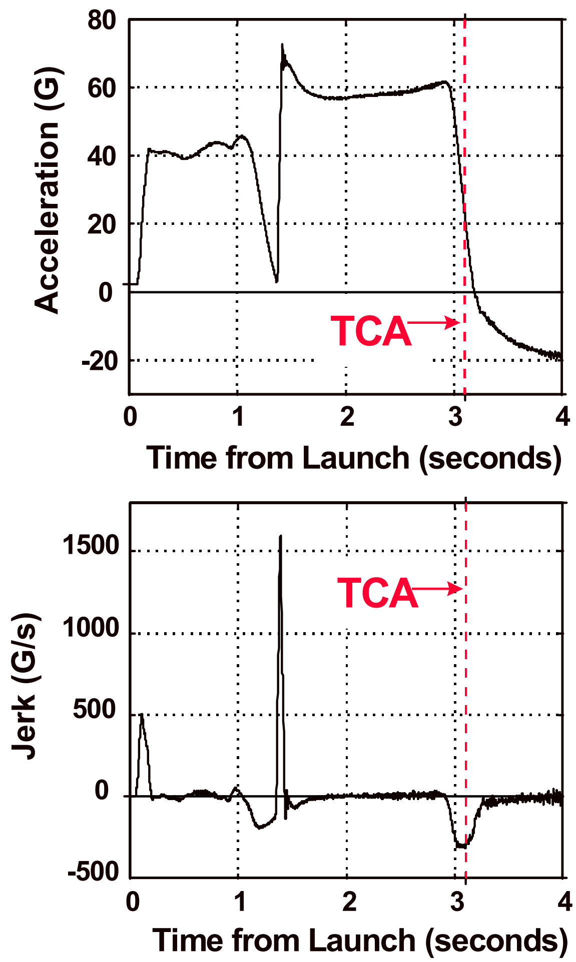

Figure 2. Sled acceleration and jerk profiles in high dynamic region near TCA.

Relative position vector differences between the GPS measurements and the optical survey are summarized in Table 1. The survey measurements combined with fiber optic and camera-processing uncertainties were assessed to produce less than one-centimeter error in the reference position used for comparison with the GPS data. The uncertainties shown in the table are those associated with the GPS measurement process. The tabulated differences can only be considered relative position errors if the surveyed data is assumed to be errorless. In any event, the differences between the reference and GPS measurements are seen to be less than two centimeters in all coordinates and were consistent with the GPS uncertainty estimates. The data clearly verify that a translator-based GPS relative measurement system can provide two-centimeter accuracy in a high dynamic environment. It was also demonstrated that this accuracy could be achieved using only a few seconds of data near closest approach.

Table 1
Relative Position Difference (GPS-Survey)

Component	Difference (cm)	Uncertainty (cm)
Along-track	1.1	0.8
Cross-track	-.03	0.6
Vertical	1.4	1.8

All the other intercept measurement issues relative to antenna design, velocity determination, and attitude were adequately addressed in the ERIS tests. The only outstanding issue was whether GPS signal tracking would allow carrier cycle range measurements in very high dynamic situations. This demonstration provided that assurance.

GPS Evaluation Capabilities

Trajectory Measurements
There is a tendency to focus attention on how well this technique will measure the point of impact. Actually the real virtue of this system is that it extends the 2cm measurement accuracy to a 3-dimensional vector uncertainty over the final relative trajectory domain. This system is uniquely capable of independent trajectory measurements of this accuracy throughout the last 10Km (or more) of interceptor and target closure.

Model Assessments
There are target-mounted sensors capable of measuring impact points to the same precision, but they provide no information for a near miss. However, understanding what caused a near miss is very important. The GPS system can address small-scale trajectory deviations that accompany a near miss that may offer critical insights into the cause. Having precise closure trajectory measurements allows independent evaluation of the seeker and control functions for all test flights, hit or miss. In the aggregate (i.e., ensemble analysis), these data should provide insights that are not available by any other means.

Lethality Assessments
Coupling accurate impact geometry data from GPS with debris cloud evaluations can support lethality evaluations. While radar or optical signatures of the debris cloud might be offered as positive indicators of a lethal impact they can't describe the geometry that produced success with the accuracy provided by GPS. Debris cloud measurements may provide important data for lethality evaluation, and they should be used to their fullest capability, and application of these techniques is strengthened when combined with GPS measurements. Differential GPS measurements provide the *string* needed to tie the various observations together. From the lethality test perspective it is useful to think of differential GPS as providing impact geometry information equal to that provided in a well-instrumented ground test. Admittedly we do not have the same level of control over the impact, but each GPS-measured impact coupled with the debris information represents *real* weapon system performance that provides a valid sample to compare with analytic impact model results. In this sense, every differential GPS instrumented flight test provides lethality test data similar to a special ground test.

GPS Uniqueness
Differential GPS is the only means that can measure the impact geometry with accuracy equivalent to what is obtained in a well-instrumented ground test. While radars can provide reasonably accurate line-of-sight measurements of range, their angular resolution is essentially useless at this accuracy and the available sites seriously limit multilateration capability. Optical instruments can provide high-resolution measurements, but their geometry is also limited by site constraints. However the most serious difficulty with optical instruments are their visibility limitations.

Translator versus Receiver

Risk of Losing Data
A primary reason for using translators is that they reduce risk. With flying receivers, if one or more phase-locked loop in either receiver drops lock at a critical time, the lost data can never be recovered. Unexpected phase jumps due to antenna motion or vehicle dynamics may easily produce these problems just when the interceptor is making its final trajectory adjustments. When dual frequency tracking data is combined in the ambiguity resolution process, eight phase-locked loops are simultaneously required (one for each frequency, for each of two satellites, and for two bodies). With flying translators, all tracking is done post-flight where reiterative processing can be applied to minimize loss of lock conditions. This capability was well demonstrated in the Holloman test. Considering the high cost of conducting an interceptor flight test, this one potential shortcoming would alone be sufficient for some of us to reject the receiver approach.

Other Translator Benefits
However, there are even additional drawbacks. Receivers: 1) are more complex, 2) require presets for initial acquisition and signal security, and 3) may be limited by time-to-first-fix when antenna visibility time is short. Also individual tracking loops within each receiver, and most surely between the two receivers, may have different and varying characteristics during

the flight. In contrast to this, a translator: 1) is a simple radio relay requiring no signal tracking or message recovery functions, 2) needs no presets or GPS security considerations, and 3) the post-flight tracking can recover data in any short span where signals exist (within tens of milliseconds of their availability). Furthermore, since the post-flight tracking is accomplished in a laboratory environment using the same receiver for both translators, the potential for varying characteristics between tracking loops is minimized. Finally it should be noted that even if the receiver works perfectly, the translator solution will still be superior. Since post-flight tracking can be iterated at will, tracking loop performance can be optimized for any particular circumstance. Tracking aids can be refined and loop bandwidths adjusted to optimally match the test flight conditions; no practical real-time receiver can provide this capability. Considering the accuracy requirements and the importance of flight test success, we conclude, that translators are the only sensible choice.

Measurement Concept

The basic elements of the needed measurement system are shown in Figure 3. Both the interceptor and target have subsystems consisting of a dual frequency GPS antenna and translator, and a downlink antenna. Each tracking station data recovery subsystem (target and interceptor) will receive and record the translated GPS signals. The recorded signal data are sent to the post-flight processing subsystem where the relative trajectory measurements are derived. Trajectories for each vehicle are obtained from multiple measurements of satellite-to-satellite differences. This technique has the benefit of removing all common mode errors beyond the GPS antennas. Absolute trajectory uncertainties of less than 2 meters in position and less than 1 cm/sec in velocity are readily achieved. However, most of the absolute error is the same in both bodies and the relative position error (i.e., the closure trajectory) is much smaller.

Very accurate relative positioning is based on using carrier phase measurements to determine the vector position difference between the target and interceptor to a small fraction of the signal wavelength. While carrier phase noise is small, phase measurements are not normally useful for ranging because they are ambiguous at the signal wavelength level (i.e., the range is known to within a fraction of 19 cm, but how many cycles there are in any slant range measurement is unknown). In the precision differential measurement, the basic data are second differences (i.e., the difference between identical satellite-to-satellite differences as measured at the two vehicles) and special processing techniques are used to resolve cycle ambiguities.

Accurate impact analysis also depends on a comprehensive description of the velocity and attitudes of the two bodies at the time of impact. Measurement of the relative velocity of the two bodies is a straightforward extension of the GPS technique used for measuring relative position (i.e., velocity is observed in the differential GPS Doppler data). Attitude measurements require additional information. In many instances, the target and interceptor have independent means for sensing attitude. As long as the attitude sensor data are available from telemetry, the attitude histories of both bodies can be reconstructed from that data. In those cases where the attitude accuracy is limited by the available sensor precision, GPS can be used to greatly refine attitude measurement precision by analytically combining the two measurements. If needed, a multiple GPS antenna configuration can extract attitude directly from GPS signals.

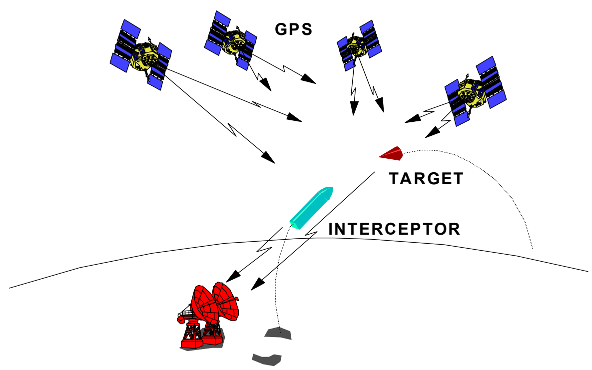

Figure 3. GPS Measurement Concept.

System Implementation

The system consists of three major subsystems: the flight (i.e., interceptor and target) subsystem, the telemetry station subsystem, and the post processing subsystem. Range investments over the last several years have developed the required telemetry station subsystem and have provided for the interface between the telemetry station and the post processing subsystem. They have also provided for development of a flight translator that is commercially available for missile flight test applications.

Flight Subsystem

Digital Translator

The Translated GPS Range System (TGRS) program has developed a family of Digital GPS Translators (DGT) that provide signals for both range safety and post processing. The DGT provides for single- or dual-frequency GPS signal translation with a variety of GPS signal bandwidths. Naturally, these translators are fully compatible with the TGRS-developed telemetry station subsystem. Adapting alternate translator designs and the telemetry station subsystem for compatibility is straightforward. There are circumstances that favor an analog translator design, and fortunately, compatible analog designs are available. The most critical and difficult integration activity may be associated with the flight subsystem antennas.

Analog versus Digital Translators

With regard to analog versus digital translators, there are several considerations. The first, and most fundamental is that the tracking performance benefits when the full 20MHz GPS signal bandwidth is translated and analog translators use downlink bandwidth more efficiently. For example, an analog system translating 16MHz of GPS signal bandwidth requires only 16MHz of downlink bandwidth, while the DGT would require 40MHz downlink bandwidth to transmit 16MHz of GPS signal bandwidth.

A second issue is related to the fact that the DGT downlink is a quad-phase-modulated data link rather than a signal relay link. The analog signal relay has a soft threshold, that is, the system performance degrades slowly and smoothly with decreasing signal. The data link synchronization requirement of the digital translator results in a sharp minimum signal level where translator signal data is completely lost. A more fundamental concern is due to the quad-phase modulation sensitivity to downlink phase disturbances. The modulated data can be lost whenever phase disturbances in the downlink path scramble the data synchronization. This has been observed to occur when the downlink signal passes through the missile motor plume or when the downlink antenna causes repeated phase discontinuities (e.g., a 2-element summed antenna on a rotating body).

Flight Antennas

Regarding flight subsystem antennas, if the translator can operate with an S-band output (i.e., there is sufficient telemetry bandwidth available), all that is added is a means for multiplexing the translator output signal with the telemetry antenna. The most desirable antenna configuration is a wrap-around phased array that has a smooth phase pattern in the roll plane. A DGT should probably not be used in cases where the missile is not roll stabilized or is configured to avoid bad phase regions with simpler antenna configurations. If the translator is moved to another frequency (e.g., C-band), a separate antenna is required. A wrap-around antenna is still preferred and with a digital translator is probably required.

The GPS antenna design is particularly important. Since satellite-to-satellite differences are used by the processing system, time and phase characteristics of all components beyond the GPS antennas are removed. However, the phase characteristics of the GPS antenna will go directly into the relative position vector solution. A good wrap-around antenna can work if the phase performance is known with sufficient precision (remember a 36 degree phase error is about 2cm). Another approach multiplexes between several independent GPS patch antennas. In most cases two or three antennas will provide adequate coverage. The multiplex switching is fast relative to the tracking bandwidth of the post tracking process, so that all antennas are tracked continually. It is desirable to use as few antenna patches as possible, because there is a multiplex loss in direct correspondence to the number of patches.

Single- or Dual-Frequency Translator

Another question associated with the flight subsystem is should the translator be single- or dual-frequency? The reason for having two frequencies on GPS is to provide correction for ionospheric propagation errors. In the missile intercept application, the ionospheric delays to both bodies are virtually identical in the region of impact. Therefore the dual frequency capability is not needed to correct for ionospheric propagation. However, the ambiguity search is greatly aided by using both GPS signals (L1 and L2). Tracking data from the two GPS frequencies are used to create computational wavelengths from the difference and sum frequencies (i.e., 86cm and 11cm). When these are combined with the range noise performance available from P/Y-code tracking (i.e., wide bandwidth range tracking), ambiguity resolution is very strong. Furthermore, the two frequencies provide redundant independent solutions, which increase the likelihood of success.

Fortunately, the two GPS signals can be overlaid in the translator bandwidth. They are easily separated in the post processing subsystem. Therefore the second frequency does not double the required bandwidth. There is a noise performance degradation associated with the overlay design, but this is still the best choice in a frequency-limited domain.

Preferred Flight Configuration

The preferred flight subsystem would be an overlay analog translator with no less than 12MHz bandwidth, a time-multiplex of 2-4 dual frequency (L1 and L2) GPS patch antennas, and a downlink wrap-around antenna array at either S-band or C-band.

Telemetry Station Subsystem

Bandwidth and Downlink Frequency

If the translator downlink is at C-band, the telemetry tracking antenna would need to have a dual frequency feed and preamplifier assembly. The TGRS GPS Translator Processor (GTP) accepts S-band inputs. Therefore it might be desirable to convert the C-band signal to an S-band frequency that the GTP currently accepts. This would be the largest modification required at the telemetry station. The GTP software would need to be adjusted to recognize the specific frequency characteristics of the new translator, but this should be a minor task. If an S-band translator is used, the tracking antenna would require no modifications, but the GTP would likely still need some adjusting for the specifics of a new translator.

If a dual frequency 6.4MHz DGT were suitable to the system requirements and the S-band could accept the 16MHz downlink for this DGT, the current telemetry station subsystem would require no modifications. This is an available option of the TGRS design. This choice does increase risk because the processing required for 2cm relative positioning has not been proven with this restricted GPS bandwidth. Furthermore, this choice requires more S-band downlink than the preferred analog translator approach. These two factors are probably sufficient to eliminate this option.

Downlink Choices

The best choice would be a 12MHz analog translator with an S-band downlink, but if this bandwidth is already too large, then modifying the telemetry station to receive a C-band translator is the next best option. The GTP recording capability is already sufficient for any option being considered.

Post Processing Subsystem

Current Configuration

The TGRS program and the Navy have already funded the interface that allows the current Trident post tracking facility to track translated signals recorded by the GTP. The current post tracking subsystem operates with the DGT and several analog translator signals recorded with GTP equipment. Adaptation to a new translator is easily accomplished.

The current post processing facility is continuing to support Trident flight tests, MDA target and probe launch vehicle tracking operations, and has this year initiated Minuteman III tracking operations. The current post-tracking subsystem is the third generation and development of the fourth generation subsystem has already begun. The tracking functions provide all the flexibility of a software receiver, but they operate at hardware rates that can even be faster than real-time rates. The system can track all normal GPS signals (L1 C/A, L1 P/Y, and L2 P/Y), translated with full or limited bandwidth. The staff that sustains and operates the facility have extensive experience in GPS receiver design and signal processing.

Benefits of Post-Flight Tracking

This is where the translator-based instrumentation system benefits are fully realized. The signal tracking operation uses the best available aiding, normally derived from the missile inertial sensor telemetry data. Tracking is completed for all in-view satellites (a typical Trident flight provides signals from about 20 satellites). All available signals are tracked (L1 C/A, L1 P/Y, and L2 P/Y). Additionally, a pilot carrier track is used to obtain an independent measure of the translator oscillator. All signal tracks are compared to their corresponding aiding data to check for divergence, and if necessary the aids are adjusted and the signals are re-tracked.

There is a good deal of redundancy in the available signals. The downlink signals are recorded for both receive polarizations and this provides complete signal redundancy. Additionally, the multiple GPS antennas have regions with overlapping coverage. All the signals are fully tracked and the tracking results are compared for any differential inconsistencies. This process is very helpful as a first test for bad tracking regions in all sets of data and it also provides a good check for carrier cycle slips in the phase-locked-loops. Furthermore the large number of satellites and the multiple antennas and frequencies are all used to assess tracking data quality and consistency. These crosschecks provide a powerful means for assessing the tracking data and help characterize the statistical characteristics of the tracking data results.

Within each track there are normal quality checks. For example, the range tracks are based on fitting the outputs of 11 range correlators, a center one and 5 evenly spaced to either side of the center. The character of the fitted range function is examined to characterize the nature of the track. Tracking noise and lock status data is examined for all tracking loops. The data is not passed to the next processing step unless all tracking consistency testing is successful. The virtue of post-tracking is that it can be refined and repeated as required.

Finally the tracking data is fully corrected. All systematic error corrections are first applied (e.g., satellite clock errors, relativity errors, etc.). The data is examined for cycle slips and normally corrected (the multiple polarization and frequency samples provide a powerful means for correcting cycle slips). Antenna model data is used to assess its impact on the tracking data and for correction, when appropriate. Next the dual frequency data is combined to remove ionospheric delays and/or to aid the cycle ambiguity process. When all reasonable data editing and correction steps are completed the resulting data goes into the final Kalman filter-processing step. The tracking data are not just the measurements of range and range rate for each satellite link; they also include a full characterization of the uncertainties in the measured data. This is done at a level of detail that just can't be achieved with a real-time receiver.

The job is not done yet. The final Kalman filter process exercises the final screen on the tracking data. Fitting residuals are examined to further test the quality of the solution, and if necessary and properly understood, further editing and/or corrections are applied. If some tracking anomaly is recognized, even in this last step, the tracking operation can be repeated. Isn't this the real beauty of post-flight tracking? Isn't this why translators are better than receivers for system evaluation work?

Conclusion

It is difficult for those of us who have done extensive post-flight missile test and evaluation work with GPS translators to understand the hesitancy to implement an adequate translator-based GPS system for missile intercept testing. As noted earlier in this paper, the translator bandwidth is fundamental to the benefit of the system. It is precisely the basis for transferring the entire signal tracking operations to the post-flight domain where the large evaluation benefits are realized. Any compromise of this characteristic moves the critical signal tracking operation back into the missile, and that both limits performance and increases risk.

Interceptor flight tests are complex and costly. Every effort should be made to collect the fullest and best evaluation data possible (the cost of the best flight-test support instrumentation is very small in comparison to the cost of conducting a test). Are we not obligated to learn as much as we possibly can from each intercept test? Incorporating wide bandwidth GPS translators in both the interceptor and target vehicles provides the only suitable trajectory measurement capability that is independent and accurate over the full end-game geometry. The range is equipped to support this instrumentation and the post processing facility is available to fully exploit all its capabilities. All that is needed is the resolve to overcome the objections so that flight subsystem implementation can move forward.

---

[1] Hattox, T. M., Westerfield, E. E., and McNellis, J. R., "Precision Determination of Trajectory and Miss Distance of ERIS Interceptor and Target (U)," SECRET, *AIAA Missile Sciences Conference (Proceedings)*, February 1993.
[2] Thompson, T., Levy, L. J., Dougherty, J. M., and Hattox, T. M., "Two-Centimeter GPS Measurement System for Missile Intercept T&E," *AIAA Missile Sciences Conference*, December 1996.
[3] Thompson, T., Dougherty, J. M., and Hattox, T. M., "Application of GPS to Two-Centimeter Test Missile Intercept Measurements," *53Annual ION Meeting*, June 1997.
[4] Thompson, T., Devereux, W. S., and Dougherty, J. M., "An Instrumentation System for Lethality Evaluation of Missile Intercept Flight Tests," August 1997.